Physical and computational modeling of airflow around buildings

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There is a paucity of experimental information concerning dispersion and infiltration of chemical and biological agents in complicated building environments. In order to predict the effectiveness of existing and proposed protective measures, proposed computer codes must predict the basic flow reliably. ***To assess the reliability of computer models for transport of chemical and biological agents in these situations, accurate measurements of the basic flow fields must be available at carefully-controlled, well-known conditions for realistic geometries***. Urban wind tunnel representations can provide useful results for a range of scales of urban terrain; however, for ***coupled interior/exterior building*** flows in realistic surroundings (Figure 1), massive use of hot wire anemometry is required and/or optical techniques must be applied -- with difficulties in measuring positions accurately due to refraction of light at the multiple building walls represented, even if the walls are optically transparent. A unique opportunity to apply optical techniques for such complex geometries exists with systems that match the refractive indices of the working fluid and the model. An advantage of such systems is that flow patterns, particle transport and velocities can be measured inside and around complex arrangements of transparent building models without disturbing the flow and without the experimental uncertainties caused by distortion. ***The INEEL Matched-Index-of-Refraction (MIR) flow system should be ideal for physical modeling and for assessment of computer models developed to predict internal building vulnerabilities to external CB attacks.***

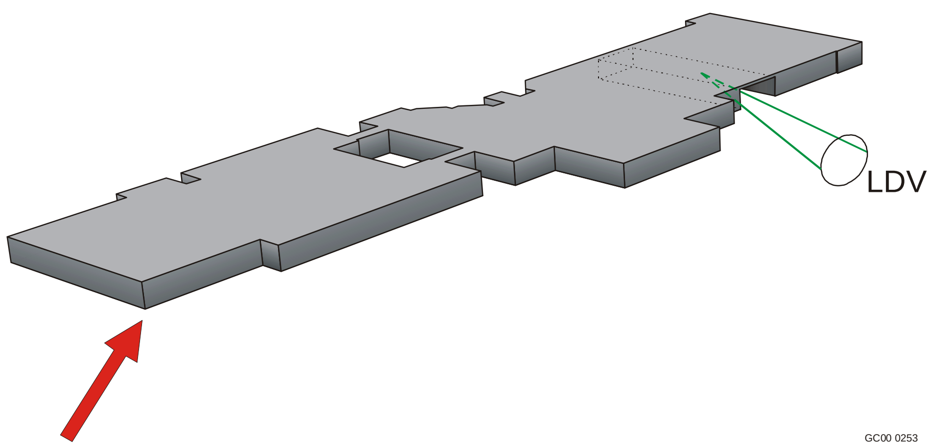

Figure 1. Example of experiment to demonstrate coupling of interior and exterior building air flows for CFD code assessment. The refractive indices of the model and fluid are matched to avoid distortion of beams from the laser Doppler velocimeter.

Means are needed to assess existing and proposed structures for vulnerabilities of buildings to a chemical or biological attack. Routes of entry for CB agents, countermeasures for vulnerable areas, positioning of early warning detection and alarm systems, designation of safe areas within the building, decontamination measures, etc. must be treated. External environmental flows affect the interior flows and, consequently, the effectiveness of agent transport into and through the building.

Conceptually, computational fluid dynamics (CFD) codes and advanced computing and visualization techniques could provide such predictions in a timely manner for the complex urban environments and buildings involved. However, the state of the art of CFD in relation to predicting flows over, around and through bluff bodies is still in an evolving stage [Rodi et al., 1997].

Solutions of these problems require reliable knowledge of the coupled external and internal flows and related transport phenomena. Conceptually, computational fluid dynamics models can provide this information. However, as anyone who compares weather reports (= measurements) to forecasts knows, time-dependent three-dimensional computer models are not inherently reliable. For example, Tuesday's forecast of Friday's weather in the newspaper can be considerably different from Friday's forecast [USA Today]. Also, in the experience of one of the authors, highly touted Direct Numerical Simulations do not necessarily give predictions in good agreement with actual measurements, particularly at first when coding errors may still be overlooked.

As indicated by Snyder [1981], MacDonald, Griffiths and Hall [1998] and others, for blunt objects such as buildings, the Reynolds number must be above a threshold value of 4000 (based on height) in order to provide ***large-scale flow similarity*** and Reynolds-number-independence. Thus, physical models of moderate size can represent key features of full-scale buildings in atmospheric flows. In particular, the external pressure distribution (which can induce or modify indoor flows) and the dominant large-eddy flow structure can be scaled.

The state of computational wind engineering has been considered in two recent international symposia at Tokyo [Murakami, 1993] and at Colorado State University [Meroney and Bienkiewicz, 1997]. As noted by Meroney [1998]: "In the most recent symposium a large number of authors reported on the use of fluid modeling to validate models and verify the integrity of various choices for modeling turbulence, boundary conditions and grid selection. The fluid model results clearly revealed that codes which justified themselves only against other codes or through numerical sensitivity tests were inaccurate and not dependable. Fluid modeling of complex building arrangements is often the only “touchstone” available to assure confidence in the extremely versatile but often untested numerical programs."

Potential users are ***code users and developers*** and the designers of ***field experiments***. Code developers need careful measurements of velocity and Reynolds stress distributions and particle motions in order to develop, calibrate, ***assess and finally validate*** their computer models. It is difficult to obtain useful velocity, Reynolds stress and agent transport data for internal and external flow fields that are coupled; the INEEL MIR flow system is ideal for this application. An advantage of matching the refractive-indices is that there is no distortion of the laser Doppler velocimeter (LDV) beams as they pass through the model and fluid [Corino and Brodkey, 1969; Budwig, 1994].

Even if model predictions compare favorably with results of field experiments for a new geometrical configuration, such agreement can be fortuitous. If models are calibrated to the measurements of field experiments for one arrangement, extension to another different configuration can give misleading predictions. To improve the model reliability, basic flow field predictions should be confirmed for each different geometry, both without the influence of a turbulence model (tests code) and with the proposed turbulence model but without other complications (tests turbulence model). The MIR flow system can provide this information for coupled interior and exterior building flows.

MIR system experiments can supplement additional data from other laboratory-scale and field experiments. Scaled geometric representations in ***urban wind tunnels*** can provide some of the detailed measurements needed. However, wind tunnel experiments ***will have difficulty*** determining interior velocities and Reynolds stress fields (induced by external flows) inside buildings of complex shapes. And, although they serve as the ultimate practical tests, ***field experiments*** typically have large scatter, have incomplete descriptions of the conditions and lack the complete range of measurements needed by code developers. Since uncertainties in the values of key flow parameters can be large in field tests, carefully controlled experiments are necessary to assess the accuracy of computational models and to guide their improvement. The MIR flow system can provide accurate, useful data for these purposes.

The availability of physical modeling capabilities can serve as insurance. Conceptually, computer models can provide information on flow fields for the design of expensive field tests. However, such test designs will be more reliable and the process will be more cost effective if the basic flow predictions of the computer models are first assessed at the geometric arrangements of the proposed field experiments. And if the assessment does not validate the models, the data from the physical modeling are available to guide the designs.

One of the most ***important aspects*** of building transport modeling is prediction of the basic flow field for different geometrical arrangements; it must be correct in order to have confidence in the ***prediction of*** other variables, such as ***temporal agent concentrations***. The MIR flow system can determine the velocities and Reynolds stresses of the basic flow field through and around buildings without the complications and uncertainties introduced by other phenomena such as compressibility, buoyant forces, etc. in the overall description.

In general, the experiments have not had the capability of measuring both interior and exterior flows for complex building environments. Experiments with the new INEEL MIR flow system would have that capability.

The recent collaborative study by INEEL and Bechtel R&D group has the objective of assessing computational fluid dynamics (CFD) models for simulation of flow around buildings -- by comparing experimental and numerical results. Experiments have been conducted in the INEEL MIR test section and related numerical predictions were developed with an appropriate commercial CFD code. An advantage of the MIR facility is that flow patterns and velocities can be measured inside and around complex arrangements of transparent building models without disturbing the flow and without the experimental uncertainties caused by optical distortion. For the experiment, a building plan was selected to represent an existing building (Figure 2).

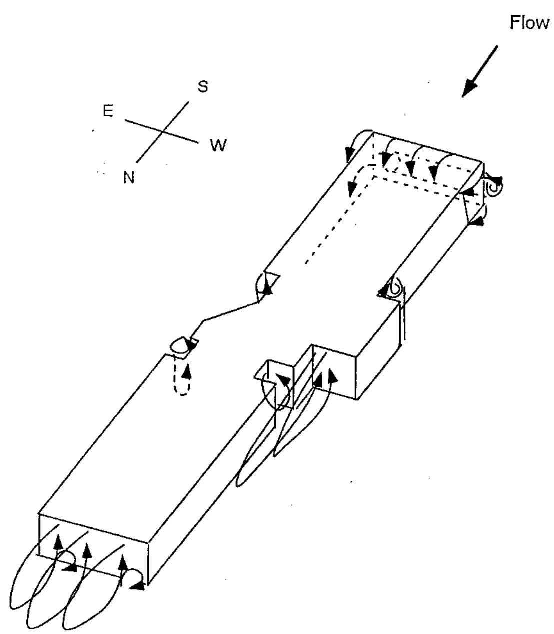

Figure 2. Building model for studies in MIR flow system with typical recirculation regions identified.

The experiment was designed to represent an appropriate building in a semi-urban environment. The outer dimensions of the plan view are approximately to scale for an existing building while the height is twice as high. The model was mounted on a plate simulating flat terrain and the side walls of the test section induced blockage and boundary layers as from nearby buildings. Upstream a turbulence-generating "fence" was installed to provide the effects of the wakes of upstream buildings. The consequent velocity profile approaching the building was a redeveloping turbulent one below a low level atmospheric jet displaced upwards by the building complex.

Two model locations with slightly different freestream velocities were chosen, giving Re ≈ 6200 and 8300. Measurements with a two-component laser Doppler velocimeter (LDV) concentrated on the upstream flow conditions, flow above the building and separated flow in recirculating regions on the sides, aft and ahead of the building (Figure 3). Data include streamwise and vertical mean velocity components and their fluctuations, U, V, u′ and v′, plus flow visualization by video and camera records of the paths of small bubbles. The upstream flow was typical of a low-Reynolds-number turbulent boundary layer with profiles of the turbulence quantities, $(u')^+$ and $(v')^+$, that are characteristic of a fully turbulent flow. ***It has been demonstrated that the approach provides means to assess capabilities of codes proposed for the prediction of exterior flows and transport around realistic building shapes***.

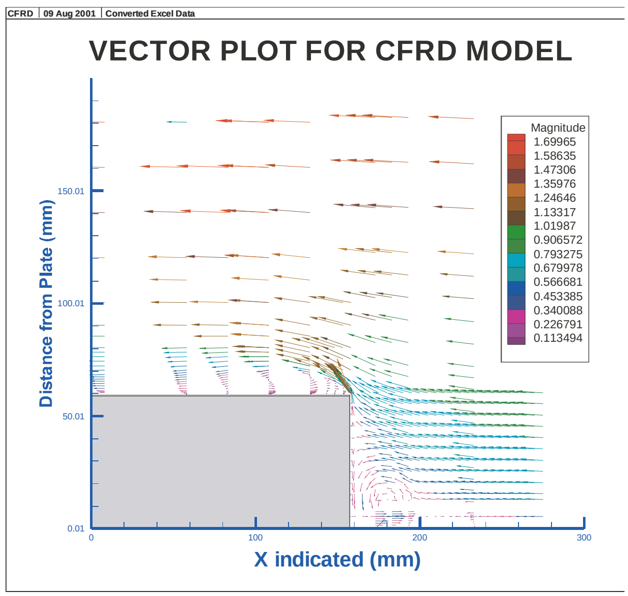

Figure 3. Measured velocity distribution above forward part of building model and upstream.

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